THz spectroscopy at TRIUMF

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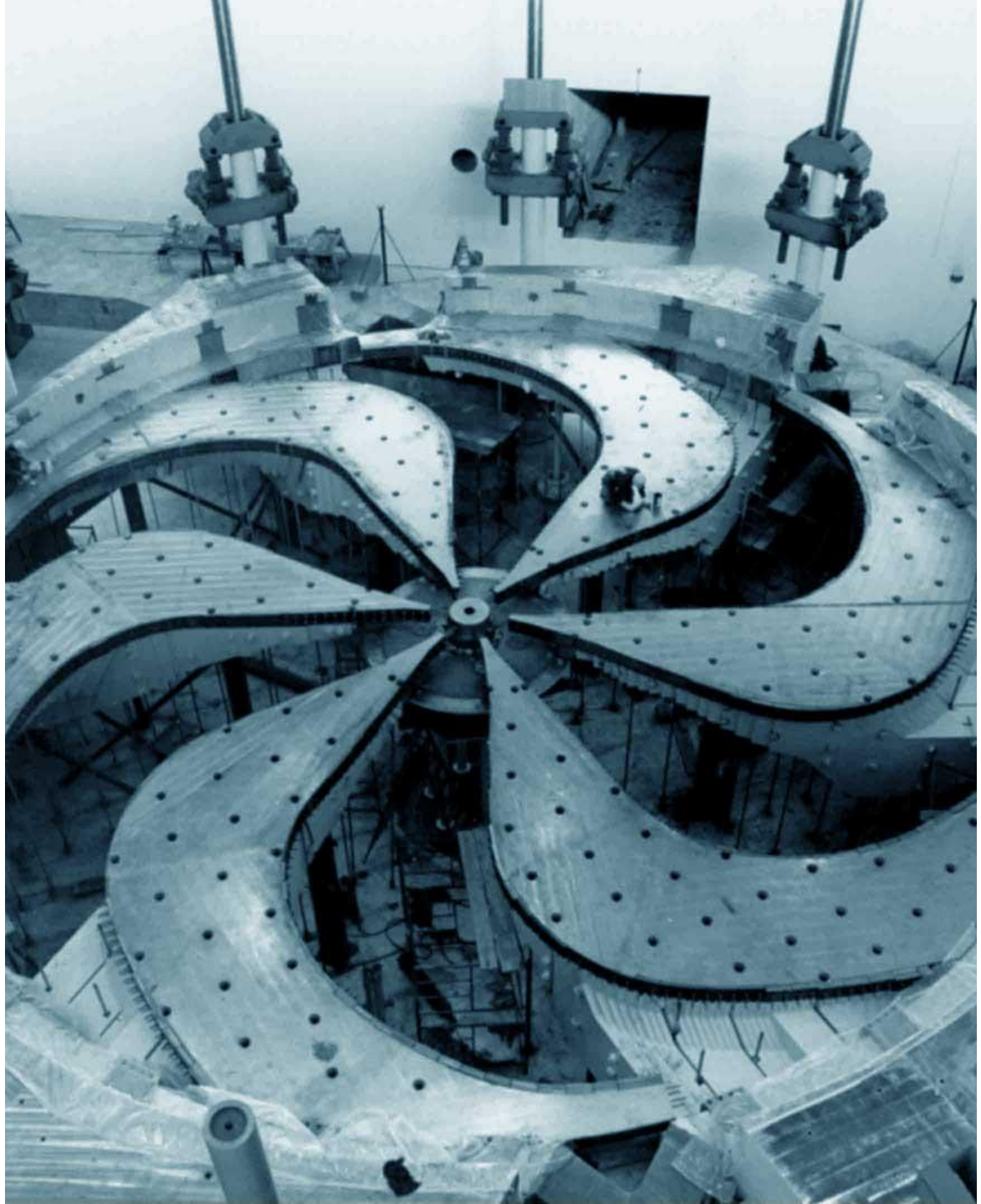
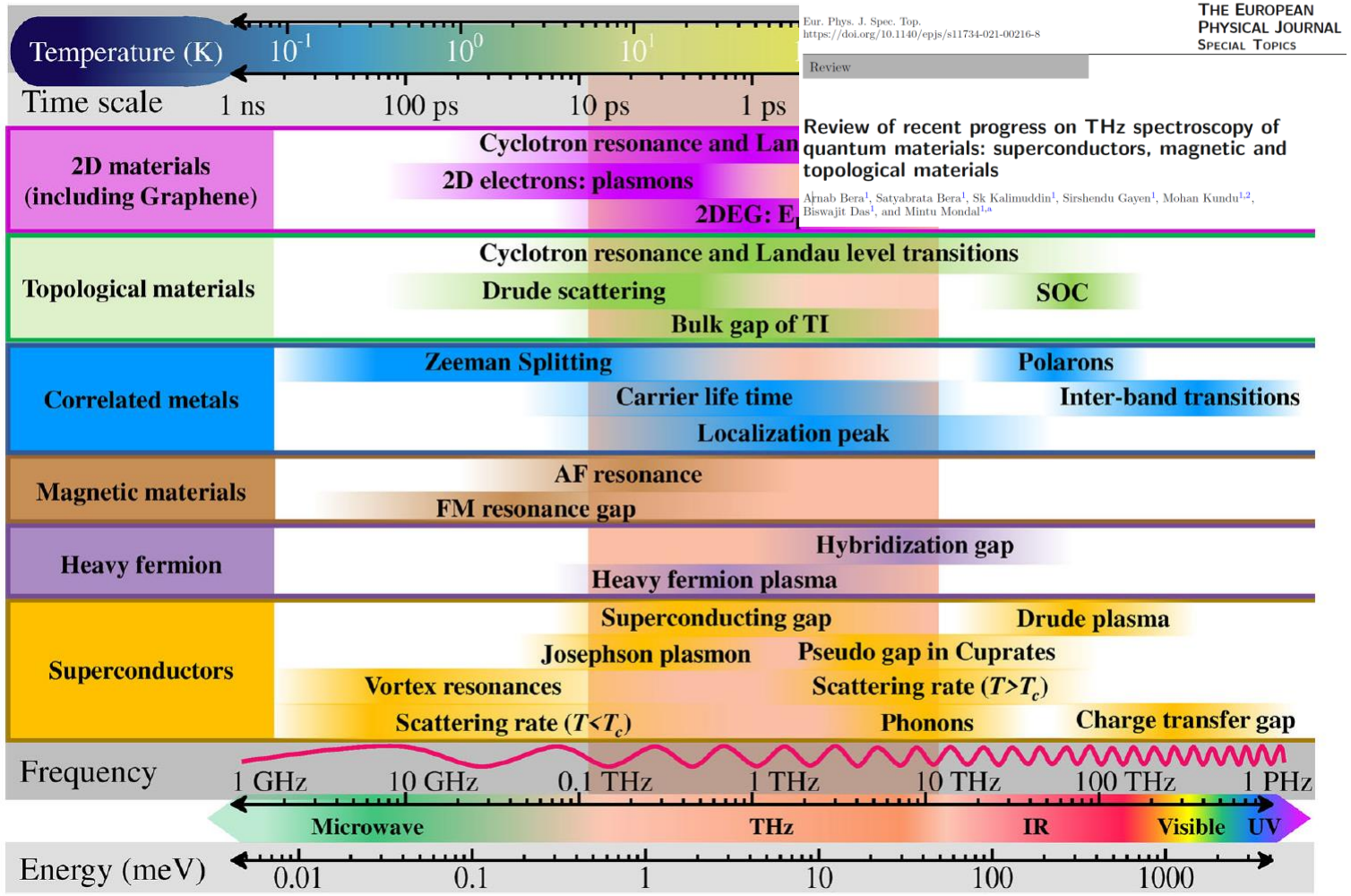
Workshop, Mar.11, 2024



2024-03-10

Discovery, accelerated

THz radiation – a popular probe to study quantum materials



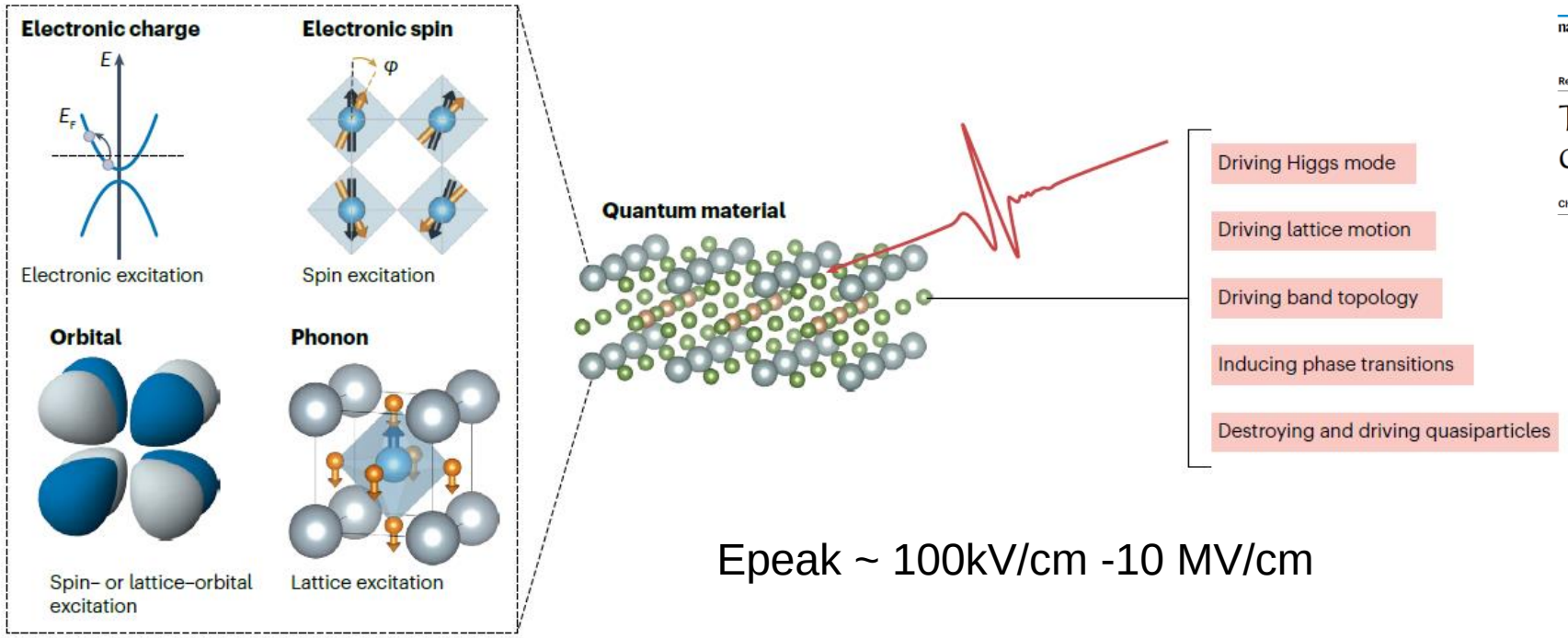
Eur. Phys. J. Spec. Top.
https://doi.org/10.1140/epjs/s11734-021-00216-8
THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS
Review

Review of recent progress on THz spectroscopy of quantum materials: superconductors, magnetic and topological materials

Arnab Bera[1], Satyabrata Bera[1], Sk Kalimuddin[1], Sirshendu Gayen[1], Mohan Kundu[1,2], Biswajit Das[1], and Mintu Mondal[1,a]

- Intriguingly, most quantum materials display collective excitations in the terahertz (THz) range of the electromagnetic spectrum.
- Therefore, THz spectroscopy has been applied to study low-energy carrier dynamics in various condensed matter systems, for example, semiconductors, superconductors, magnetic and topological materials
- The THz radiation is used as a probe to provide valuable insights through measurement of material/optical constants, the complex conductivity $\sigma(\omega)$, and the dielectric constant, $\varepsilon(\omega)$

THz radiation – a tool to control quantum materials



nature reviews materials
https://doi.org/10.1038/s41578-023-00566-w
Review article
Check for updates

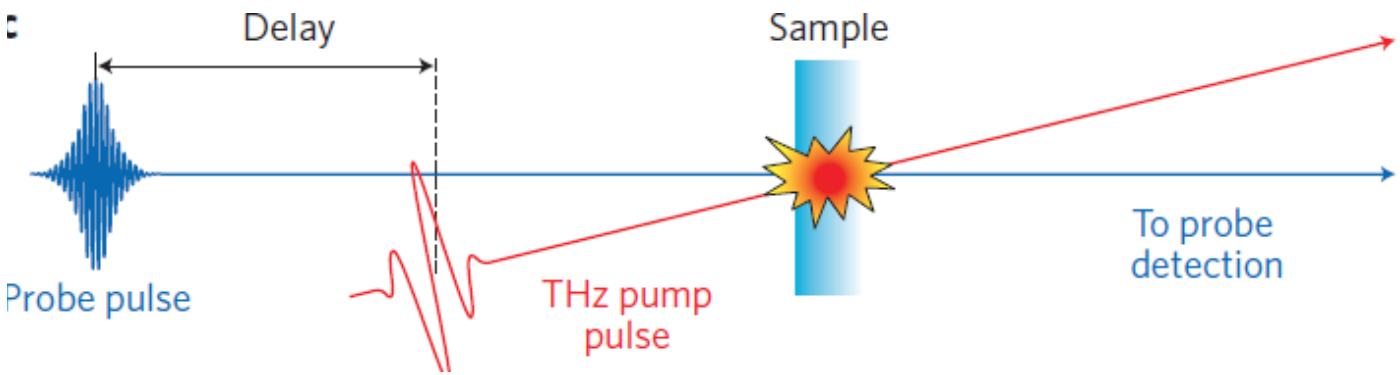
Terahertz control of many-body dynamics in quantum materials

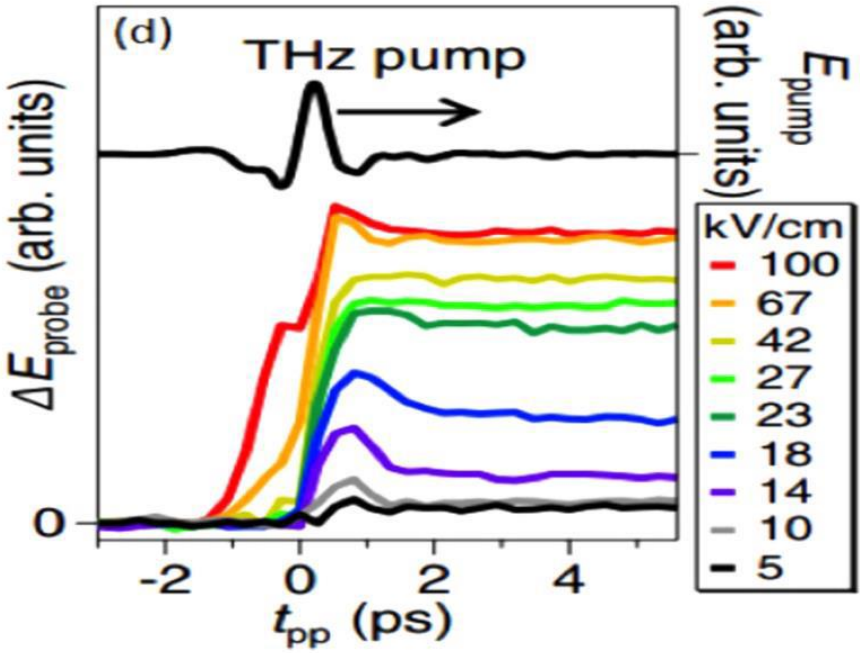
Chia-Jung Yang[1], Jingwen Li[1], Manfred Fiebig[1] & Shovon Pal[2]

Epeak ~ 100kV/cm -10 MV/cm

- THz pulses have been deployed to drive new types of non-equilibrium states of matter in a linear or nonlinear way, depending on the strength of the THz electric field.
- It is now possible to use THz radiation as a pump to selectively excite either the single particle or the collective modes of emergent phases, exciting the system to a non-equilibrium phase and then tracking it in real time as it decays back to the equilibrium phase.

Pump-probe concept

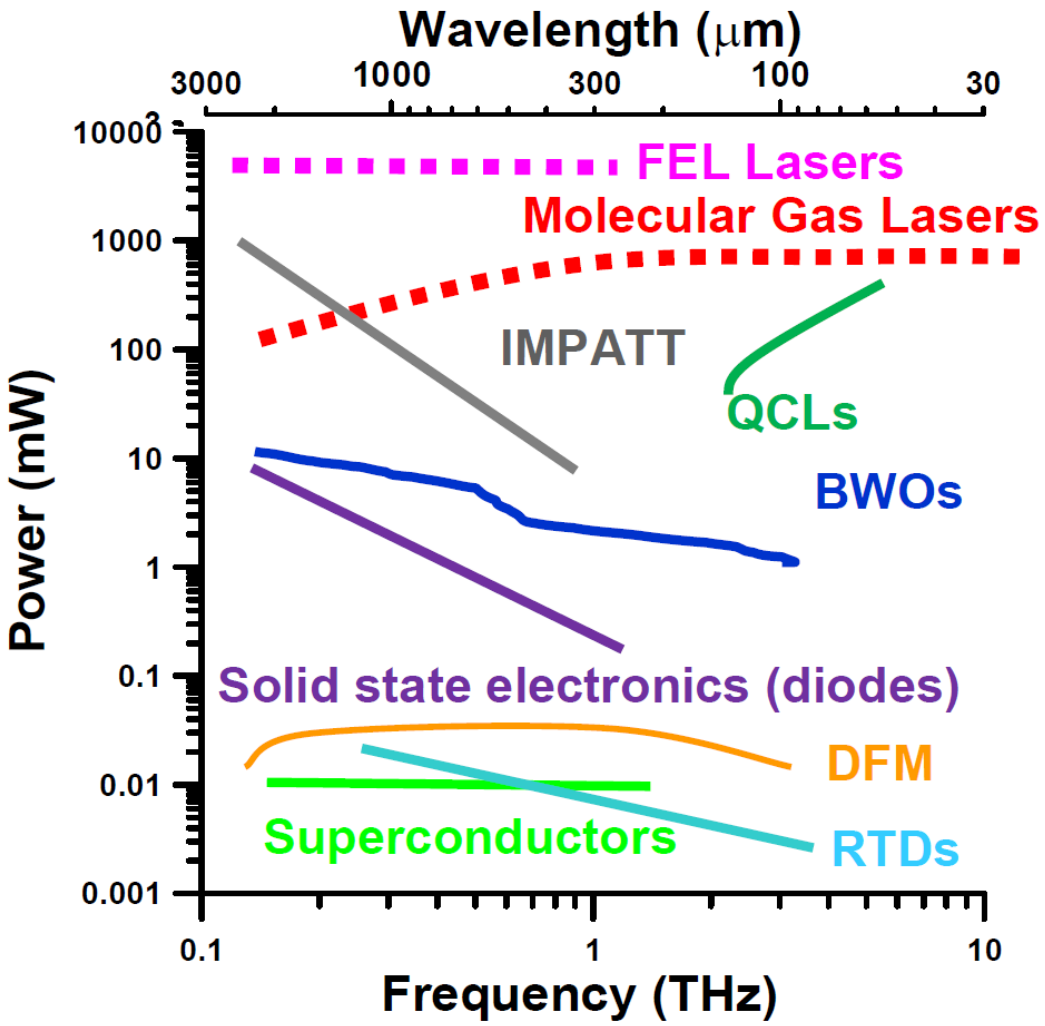




An intense THz fields can lead to a breakup of Cooper pairs in superconductors, providing a switching from superconductor to normal metal. Ultrafast dynamics of the BCS state in a conventional NbN superconductor (with a BCS gap of 5.2 meV (1.3 THz)). Matsunaga et al., Phys. Rev. Lett. 111, 057002 (2013)

- The availability of intense THz pulses and the ability to precisely measure them in a time-resolved manner enable the study of the non-equilibrium states of quantum materials.
- The potential approaches for achieving THz control of many-body dynamics include optical pump–THz probe, THz pump–THz probe and THz pump–optical probe.
- These approaches cover both resonant and non-resonant excitations of quantum states.

THz sources



- It is accepted that the THz frequency band spans from 0.1 THz - 10 THz
- Available THz sources can be divided into several categories
  - Electronic devices
  - Laser based sources
  - Accelerator based sources (FEL, Synchrotrons)

TRIUMF THz source project

- With the construction of the TRIUMF electron linac an opportunity arose for production of intense THz radiation and the corresponding staged proposal was formulated.
- The present stage of the proposal aims to demonstrate production of high–field THz broadband pulsed radiation based on coherent photon emission of the electron beam from TRIUMF electron linac and pave a path towards user experiments.
- The proposal is a part of the National FEL program led by UW and received CFI support this year.

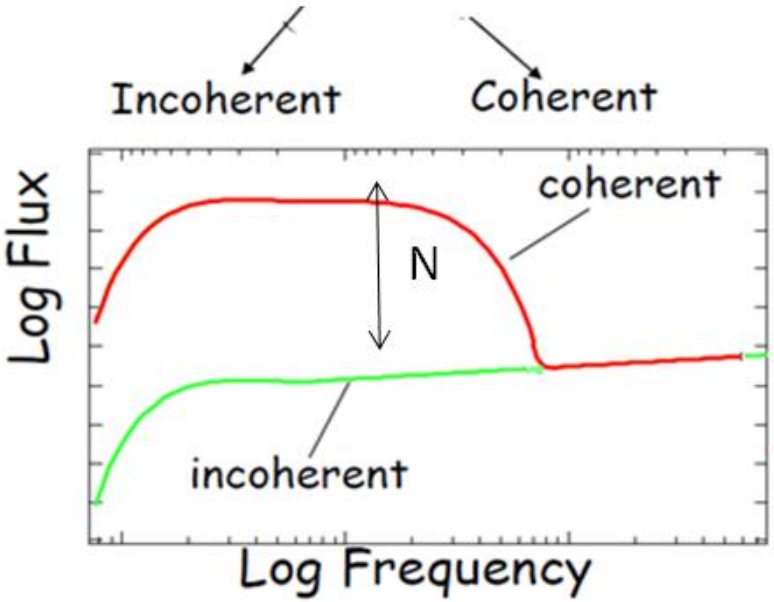
Coherent action what counts

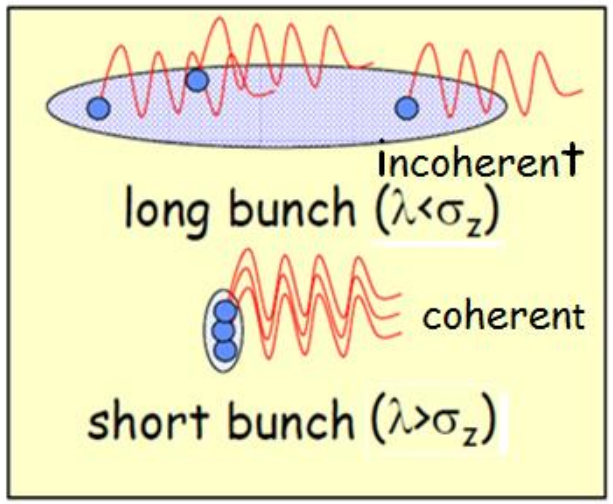
In particle accelerators beams usually exist in a form of trains of very small (~mm) bunches.

From very basic principles and valid for any electromagnetic radiation by an ensemble of charged particles !

$$I_{tot}(\omega) = I_e(\omega)\left(N + N(N-1)f(\omega)\right)$$

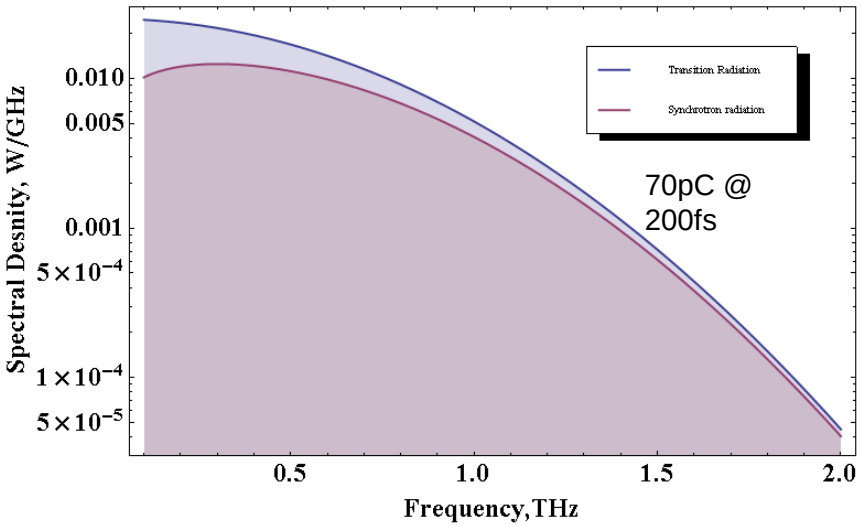
$$f(\omega) = \left|\int_{-\infty}^{\infty} dz S(z) e^{i(\omega/c)z}\right|^2$$





High charge ~nC short ~0.1λ bunch is required for a powerful source. Coherent enhancement is ~ 10^8 to 10^9

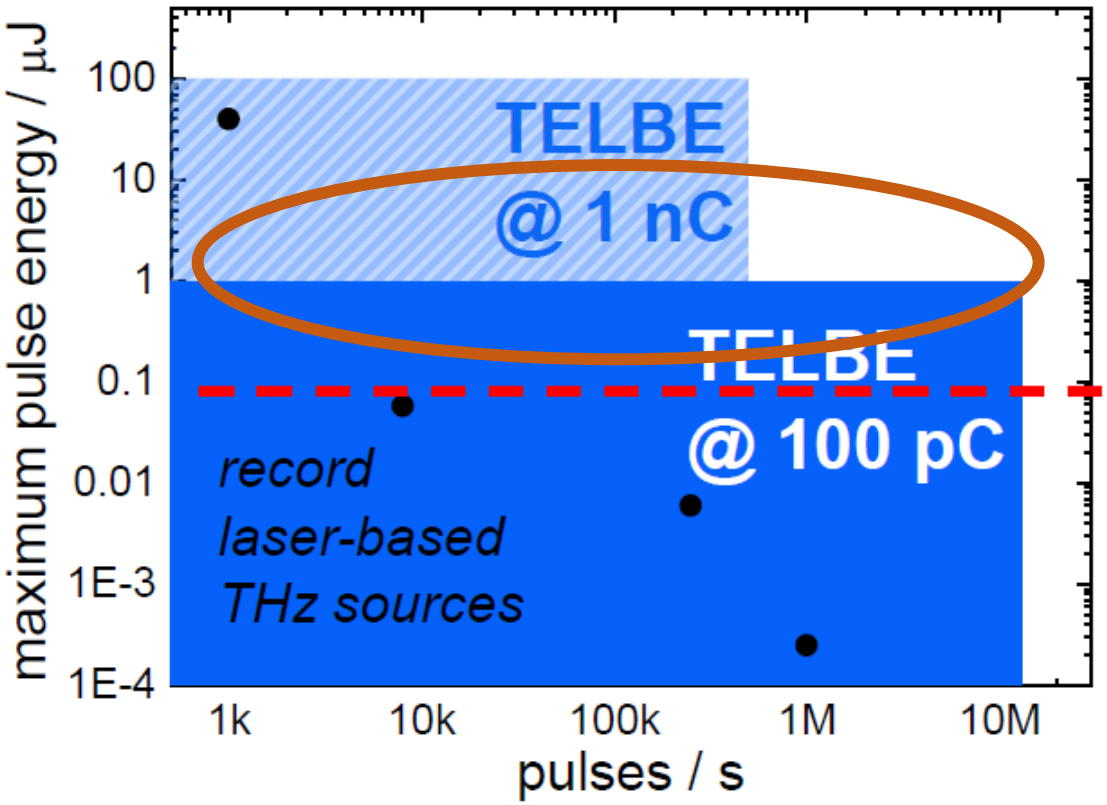
Broad band THz radiation



- Radiation spectrum is essentially broadband with characteristics that are determined by the electron bunch charge and dimensions
  - shorter beam size generates shorter wavelengths!
- Bunch charge and dimensions are adjustable but interdependent. Typically, smaller bunch dimensions dictate lower charge
- 70pC bunch charge and 70um bunch length are considered as baseline parameters

Radiation mechanism	Total power, W	Energy per pulse, uJ	Pulse rep rate, MHz
Transition radiation	30	3	<10
Synchrotron radiation	21	2	<10

Design goal parameters

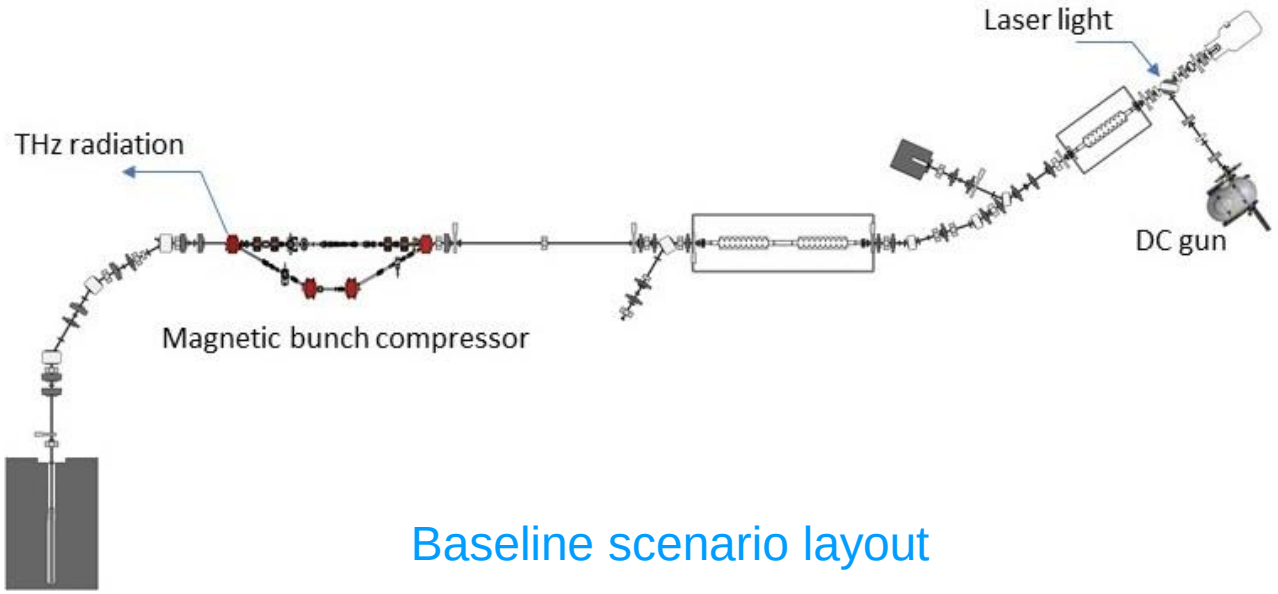


Bunch Charge	Radiation pulse energy
100pC	~ µJ
200pC	~ 10 µJ
1nC	~ 100 µJ

Few 10s µJ correspond to ~ 1MV/cm
which is of interest to high-field applications

>200pC bunches of ~ 0.1mm long
with up to ~ MHz rep rate are required.

TRIUMF THz project scope

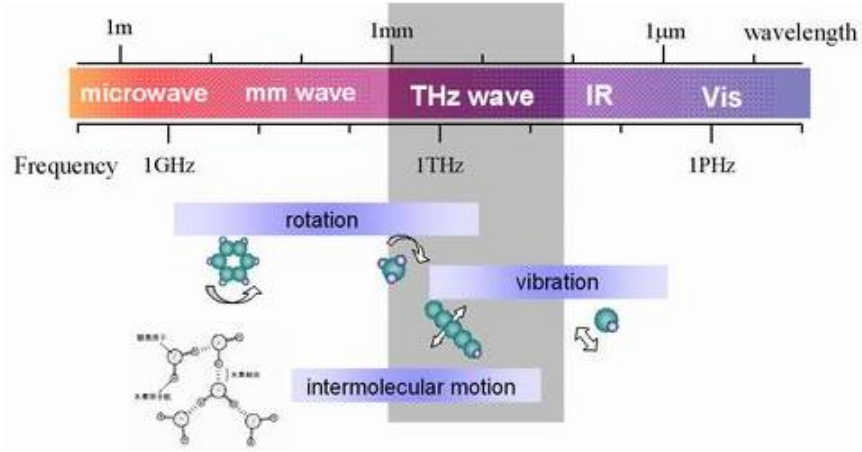


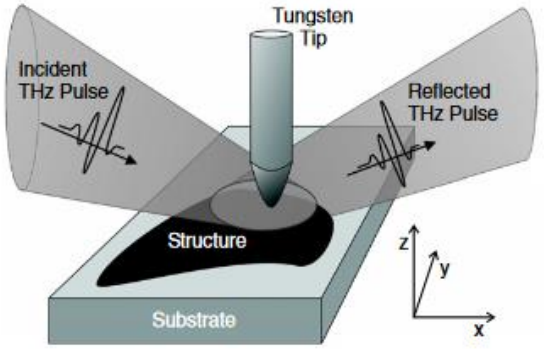
Baseline scenario layout

- Construct an electron source capable of generation of short and high-charge bunches.
- Produce electrons with a new high-brightness electron source, accelerate them and compress with a magnetic compressor.
- Generate THz radiation and characterize it.

Other THz applications

- Linear spectroscopy
  - Many molecules have structural absorption resonances at THz frequencies
  - Many fundamental excitations in condensed matter are in the THz region
- High-field Nonlinear Spectroscopy
  - Not only to probe but to control the matter
- Imaging, including microscopy
- Biological and Medical applications
- Industrial applications



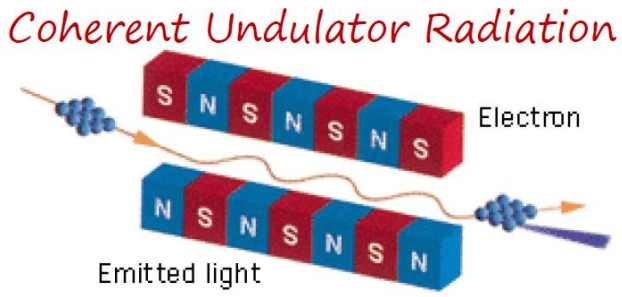


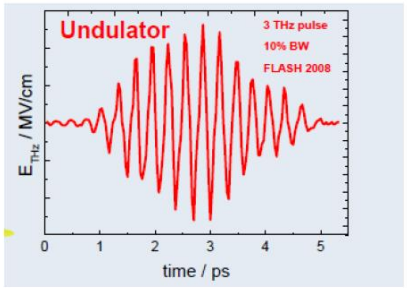
Possible synergies with other TRIUMF programs

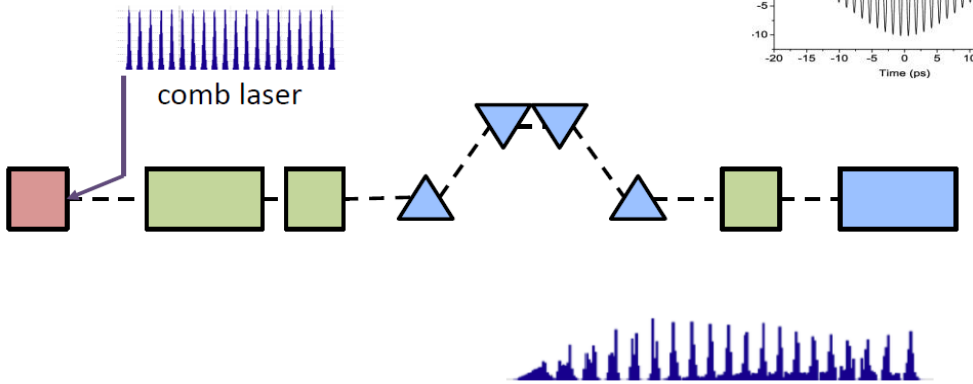
- Combination of THz radiation with other techniques accessible at TRIUMF may open unique opportunities not available elsewhere.
- In the first place this is the use of a THz pump with various probes
  - Muon probe
  - Electron probe
  - Positron probe
  - Neutron probe
  - X –ray probe
- Simultaneous application of THz probe with other probes to study several modes simultaneously

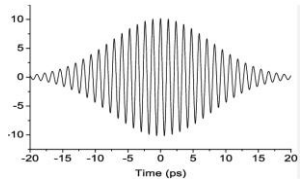
Future plans

- Possible next CFI round will focus on a THz laboratory
- Simultaneous operation of THz source and ARIEL has to be addressed as well.
- Multicycle THz for resonant excitation









Summary

- THz radiation is a promising tool to study quantum materials both as a probe and a pump
- TRIUMF started construction of an intense THz source based on a coherent emission of electrons from the electron linac
- Combination of the THz radiation with other TRIUMF material science programs may open new opportunities
- Future plans are taken shapes

Thank you
Merci

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